Coronary MRA

René M. Botnar PhD[1], Warren J. Manning, MD[2,3]

[1]Department of Nuclear Medicine, Technical University Munich, Munich, Germany

[2]Department of Medicine (Cardiovascular Division) and the [3]Department of Radiology, Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, MA, USA

Introduction

Over the last decade, coronary magnetic resonance imaging (MRI) has evolved as a potential replacement for diagnostic x-ray angiography in the evaluation of patients with suspected anomalous coronary artery disease and coronary artery aneurysms. In addition, coronary MRA has currently reached sufficient maturity such that it may obviate the need for routine invasive x-ray angiography in the assessment of native coronary vessel and bypass graft integrity. The major advantages of MRI over other coronary imaging modalities (i.e. x-ray angiography, multidetector computed tomography (MDCT)) include the absence of ionizing radiation, lack of need for exogenous contrast agents, the ease and safety of repeated studies as well as the potential to combine coronary MRA with assessment of coronary blood flow, cardiac anatomy, function, perfusion and viability (the comprehensive cardiac exam). In this review, we will briefly discuss the technical challenges and general imaging strategies for performing coronary MRA.

Technical Challenges and Solutions

Coronary MRA remains technically challenging due to several unique issues including the small caliber (3-5mm diameter) and tortuosity of the coronary arteries, their near constant motion during both the respiratory and the cardiac cycles, and the surrounding signal from adjacent epicardial fat and myocardium.

Cardiac motion

Bulk epicardial motion is the major impediment to coronary MRA and can be separated into motion related to direct cardiac contraction/relaxation during the cardiac cycle and that due to superimposed diaphragmatic and chest wall motion. To compensate for contractile cardiac motion, accurate electrocardiographic (ECG) synchronization and QRS detection are an absolute necessity in combination with patient specific trigger delays and acquisition window durations[1,2]. Data acquisition is typically performed in periods of minimal coronary motion, either end-systole or mid-diastole (**FIGURE 1**). In contrast to cardiac CT approaches which require a slow heart rate (due to the fixed acquisition interval of ~85-200ms)[3], coronary MRA acquisitions can be tailored to the patient's natural heart rate. Both methods currently require the subject to be in

sinus rhythm although MR can handle heart rate variations to a certain degree by the use of arrhythmia rejection algorithms[4]. The drawback of this gating method is prolonged scan times.

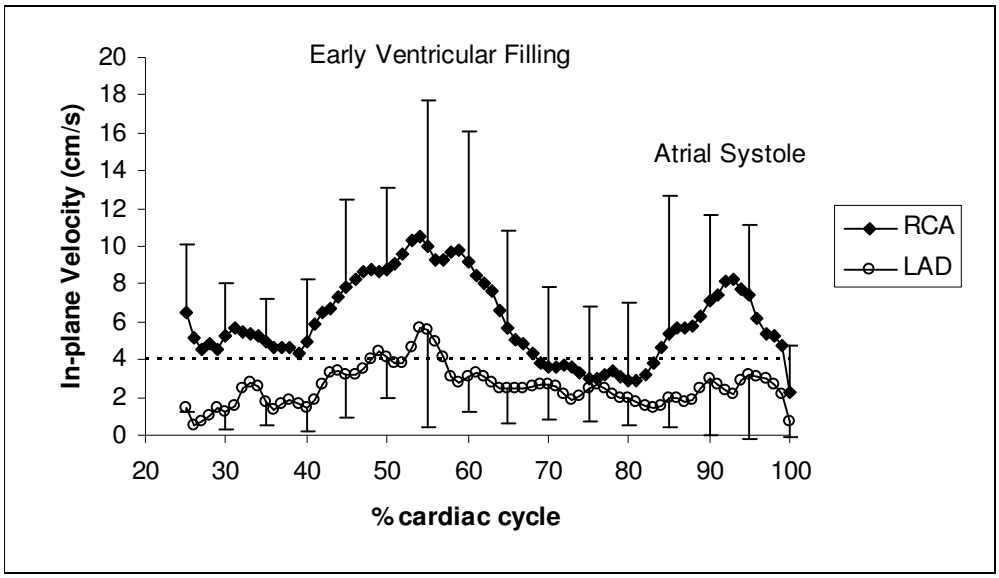

FIGURE 1: *Average velocity of left (LAD) and right (RCA) coronary artery throughout the cardiac cycle. Coronary MRA is typically performed during mid-diastole when coronary motion is minimal. In patients with rapid heart rates, end-systole may be an alternative. (courtesy: Yong Kim, MD PhD)*

Respiratory Motion

During expiration, the diaphragm ascends in the foot-head direction and the chest wall circumference decreases – resulting in a superior displacement of the lung-liver interface[5]. Suppression of respiratory motion artifacts can be achieved with several approaches including prolonged breath holding[6-9] and navigators.[10-12] These techniques track an interface that moves with respiration (**TABLE 1**). Navigator implementation varies greatly among the major CMR vendors, but free breathing right hemi-diaphragmatic MR navigators (**FIGURE 2, 3**) appear to be preferred, especially for those with coexistent pulmonary disease[13].

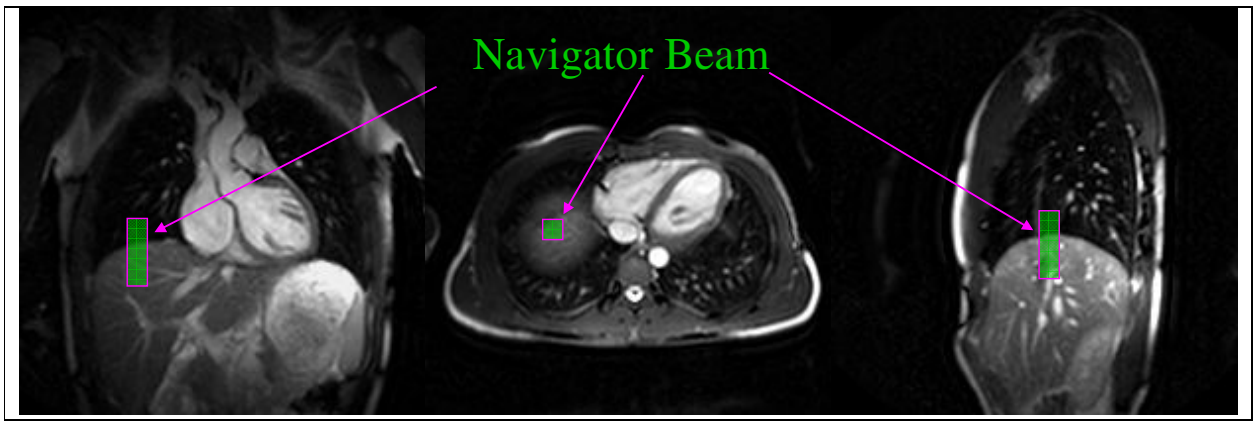

FIGURE 2: *Coronal, transverse, and sagittal view demonstrating navigator positioning on the dome of the right diaphragm.*

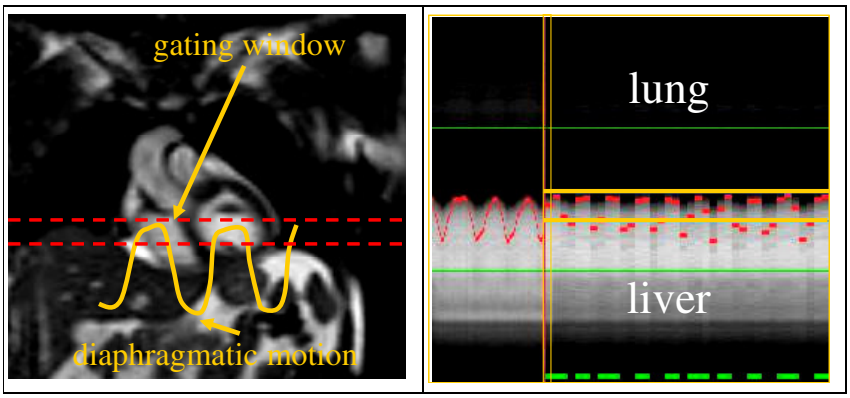

FIGURE 3: *A) Coronal view of the heart and diaphragm with superimposed respiratory motion as measured by the navigator. B) Navigator display on scanner user interface demonstrating navigator preparation phase for automatic gating window placement and subsequent navigator performance during data acquisition. Data are accepted (green dots) when the diaphragm is within the gating window, otherwise they are rejected and reacquired.*

Spatial Resolution

The desired spatial resolution greatly impacts signal-to-noise (SNR) as well as scan duration. Coronary MRA spatial requirements depend on whether the goal is to simply identify the origin and proximal course of the coronary artery (for suspected congenital anomalous coronary disease), or to identify focal stenoses in the proximal and middle segments. For the former, spatial resolution of ~1.5mm is sufficient, while for the latter a resolution ≤1mm is preferred.

Suppression of Signal from Surrounding Tissue

The intrinsic contrast between the coronary blood pool and the surrounding tissue (myocardium, epicardial fat) can be manipulated using the in-flow effect for gradient echo sequences and by the application of MR pre-pulses to suppress signal from epicardial fat[8,14] and underlying myocardium[8,15,16].

The incremental impact of epicardial fat saturation, cardiac and respiratory motion suppression and myocardial tissue suppression is displayed in **FIGURE 4**.

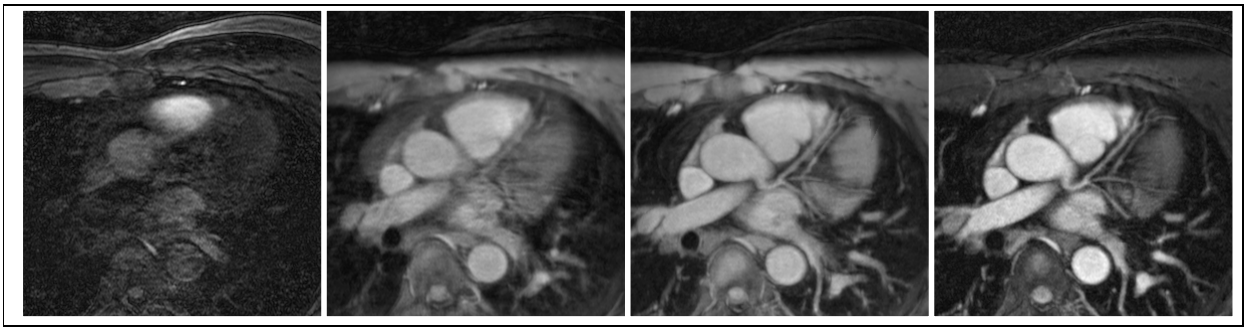

FIGURE 4: *A) No triggering B) ECG triggering C) ECG triggering and navigator gating and correction D) ECG triggering, navigator gating and correction, and T2 preparation (courtesy: Matthias Stuber, PhD)*

Coronary MRA Imaging Sequences

Coronary MRA sequences can be conceptualized as a building block (**FIGURE 5**) of components that include **(1)** ECG gating for cardiac motion suppression, **(2)** respiratory motion

suppression (breath-holding, respiratory bellows, navigators), **(3)** prepulses to enhance contrast-to-noise ratio (CNR) of the coronary arterial blood from surrounding tissue (fat saturation, T2 preparation, MTC, selective „tagging“ of blood in the aortic root, exogenous contrast agents), and **(4)** image acquisition that optimizes coronary arterial SNR.

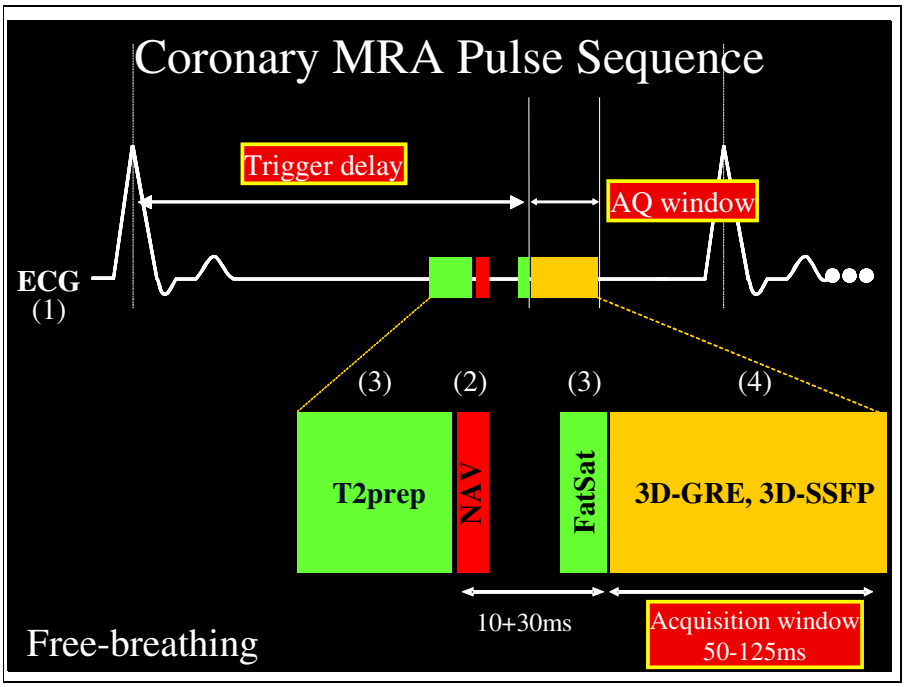

FIGURE 5: *Schematic of coronary pulse sequence demonstrating the four building blocks a typical coronary MRA sequence consists of. 1) ECG gating 2) respiratory motion gating 3) prepulses for suppression of signal from epicardial fat and myocardium 4) imaging sequence.*

Over the past decade, coronary MRA has migrated from breath hold 2D gradient echo (GRE) imaging[7,8] to navigator-based methods[10-12] using “targeted” 3D gradient echo[17], followed by “targeted” 3D steady state free precession (SSFP)[18,19], and most recently volumetric “whole heart” approaches[20] somewhat analogous to cardiac MDCT. The superior SNR and post-processing capabilities of 3D coronary MRA make it particularly attractive, though the coronary MRA post-processing tools are not as advanced as those of cardiac CT. In addition, MR contrast agents have been widely accepted as a preferred approach for MR imaging of every other vascular bed and is an area of intense research investigation for coronary MRA.

Contrast Enhanced Coronary MRA

Contrast enhanced first pass 3D angiography has become the technique of choice in the majority of vascular beds due to the excellent visualization of the arterial and venous vasculature and the good post processing capabilities. In contrast, extracellular contrast agents have not reached the same acceptance for visualization of the coronary artery tree yet, mainly due to incompatibility of the rapid passage of the bolus and the long scan times required for sub-millimeter coronary MRA. For high resolution coronary MRA, intravascular contrast agents seem to be better suited because of their relatively long half life time thereby removing the time constraints and allowing for free breathing sub-millimeter approaches. Typically, the imaging

sequence used for contrast enhanced coronary MRA consists of a non-selective inversion recovery prepulse for myocardial signal suppression followed by a 3D gradient echo sequence[21-25] resulting in an improved CNR between blood and myocardium compared to non-contrast coronary MRA.

Coronary MRA at 3T

Coronary MRA at 3T is an area of intensive research, especially in the context of parallel imaging and multi channel receiver technologies. Early studies at 3T have demonstrated the feasibility of coronary MRA using a free-breathing spoiled 3D gradient echo technique[26]. In subsequent studies, various imaging sequences such as real-time spiral imaging[27], SENSE accelerated spoiled 3D GRE[28] and 3D SSFP[29] sequences were investigated. At the present time, 3D GRE sequences seem to provide most consistent image quality but as the field is evolving rapidly, 3D SSFP sequences may become the technique of choice in the years to come. The major impediments of 3T coronary MRA are field inhomogeneities due to suboptimal shimming and increased RF penetration, thereby often limiting the shortest possible repetition time (TR). Short repetition times are, however, essential for artifact free imaging using SSFP imaging techniques. Thus, further progress is necessary before this technique will find wider acceptance.

Parallel Imaging

Parallel imaging[30,31] is of great interest for coronary MRA because of the potential of reducing the overall scan time and/or increasing the volume of interest. Until recently the use of parallel imaging in thin slab coronary MRA was limited because of the intrinsic loss of SNR. With the introduction of large volume coronary MRA[20] and the advent of 3T MR scanners, parallel imaging has finally entered the arena of coronary MRA. Sensitivity encoded whole heart coronary MRA was first demonstrated by Weber[20] and co-workers and later evaluated in the clinical setting by several groups[32]. With the introduction of 32 channel receiver systems, massively accelerated coronary MRA has become feasible and whole heart imaging in a single breathhold was demonstrated using a cardiac optimized 32-channel phased array coil and a prototype 32-channel spectrometer[33]. Acceleration factors between 8 and 12 could be achieved without major degradation in image quality. With the wider spread availability of such systems, further improvements are expected in the years to come.

Summary

Over the past decade, coronary MRA has been transformed from a scientific curiosity to a clinically useful imaging tool in selected populations – including anomalous coronary arteries, coronary artery aneurysms, and the assessment of coronary artery bypass graft patency. Coronary MRA also appears to be of clinical value for assessment of native vessel integrity in selected patients, especially those with suspected left main/multi-vessel disease. Among patients referred for x-ray angiography, a normal coronary MRA strongly suggests the absence of severe multi-vessel disease. Technical and methodological advances in motion suppression, along with increasing clinical experience will no doubt facilitate improved visualization of the distal and branch vessel. In the years to come, data from multicenter trials will continue to define the clinical role of coronary MRA.

TABLES

TABLE 1: Respiratory Suppression Methods

Breath Holding

Sustained end-expiratory breath hold
Hyperventilation
Supplemental oxygen

Free Breathing

MR Navigators

location:	Right hemidiaphragm vs. left hemidiaphragm
#NAV's	Single vs. multiple navigators
real-time:	Prospective vs. retrospective navigator triggering
correction:	Navigator triggering vs. navigator gating with real-time motion correction

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